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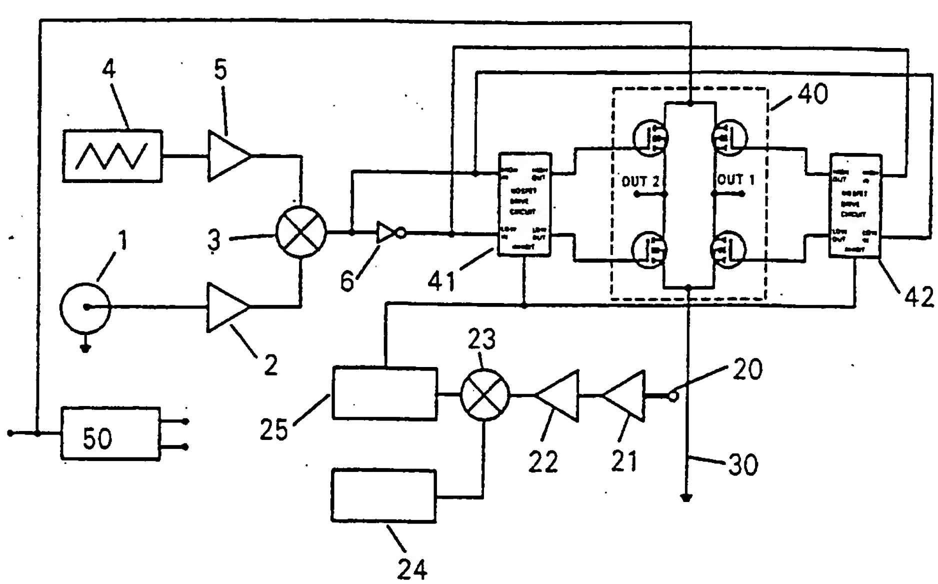
(54) Title: IMPROVEMENTS IN AND RELATING TO TRIANGLE WAVE GENERATORS AND POWER AMPLIFIERS



(57) Abstract: A power amplifier is provided with a novel triangle wave generator (4) in which a more precise triangle wave is produced with the aid of logic circuits. The resulting generator (4) is able to operate at higher frequencies. A fast current sensing arrangement is then required for protecting conditioning circuitry (40) against over-current. This is achieved with a combination of a sensing coil (20) sensing the transistor current through conductor (30). The resulting amplifier can be powered by DC and used to amplify a sine wave for DC to AC conversion.

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Improvements in and relating to triangle wave generators and power amplifiers

The present invention relates to the generation of triangular waveforms, to power amplifiers such as those used for audio amplification, and to DC to AC power generators including a power amplifier.

Known Class D power amplifiers for audio amplification typically compare the incoming audio signal with a higher frequency triangular waveform to generate a pulse width modulated signal. The accuracy of the triangle waveform in terms of slope linearity and precision of the peaks and troughs is critical to the operation of the amplifier. Inaccuracies are generally worse the higher the frequency and therefore the frequency range of amplifiers is limited. As a result, high frequency components of the audio signal may be inaccurately reproduced.

To minimise the distortions of the triangle waveforms at higher frequencies current triangular waveform generators limit the amplitude of the triangle wave. This makes errors in the pulse width modulated signal due to input signal noise more significant and hence, degrades the replication of the input signal. US-A4539693 discloses a bit synchronisation arrangement for a data modem including an oscillator supplying a triangular internal signal. Here the output of an integrator is supplied to a comparator and the output of the comparator is fed back to the integrator via an inverter provided to improve the linearity of the comparator signal. The comparator and inverter together form a bistable circuit.

The improvements suggested below enable high amplitude, high linearity and high frequency generation of triangular waveforms.

One aim of the present invention is to provide a triangle wave generator which produces an accurate triangular waveform.

Thus, one aspect of the invention provides a triangle wave generator comprising a comparator and an integrator, the output of the comparator being supplied to the integrator and the output of the integrator being supplied to the comparator whereby the output of the comparator is a square waveform and the output of the integrator is a triangular waveform, wherein the output of the comparator is supplied to the integrator via one or more bistate devices such as one or more logic gates, possibly CMOS devices. The devices are preferably arranged in a non-inverting configuration. The output of the integrator may be supplied to DC offset adjustment means comprising a variable resistor for example.

Means may be provided for adjusting the mark to space ratio of the triangular waveform, preferably also in the form of a variable resistor. One or both of the variable resistors may be laser trimmed to provide the exact required characteristics.

The present invention also provides an amplifier and a power converter including the aforesaid triangle wave generator.

A more accurate triangle wave generator is able to operate at higher frequencies. However, higher frequencies place more demand on the amplifier switching circuitry and thus it is desirable to provide a fast acting current sensor for use in protecting the circuitry against over current.

Thus, another aspect of the present invention provides an amplifier comprising signal conditioning circuitry including at least one transistor, in which means are provided for sensing the current through the transistor, said current sensing means comprising an inductor positioned adjacent to a conductor carrying the current to be sensed and an integrator arranged to integrate the current.

As calculations to be presented below will show, the integrator should preferably be arranged to integrate the current flowing through the inductor for a time greater than the turn-on time of the transistor whereby to obtain a measurement of the voltage induced in the inductor. This voltage is related to the current flowing through the conductor.

The inductor may be a single conductive loop. Thus, the current sensing arrangement comprising inductor and conductor can be readily printed on a circuit board. As noted above, the purpose of the current sensing is to protect against over current in the switching circuitry and thus means are preferably provided for switching off the amplifier in the event that the output from the integrator exceeds a predetermined threshold. Such means may produce an inhibit signal which is supplied to the switching circuitry.

An amplifier as described above, preferably including the novel triangle wave generator, may be used in DC to AC power conversion.

Thus, another aspect of the invention provides a power converter for generating an AC voltage from a DC supply comprising a sine wave generator operating at the desired frequency of the AC voltage, a triangle wave generator operating at a higher frequency than the sine wave generator, means for mixing the outputs of the sine wave and triangle wave generators to produce a pulse width modulated signal at the higher frequency, an amplifier for amplifying the pulse width modulated signal and a filter for filtering out the higher frequency.

Such a power converter could be used in numerous applications including, in particular, generation of a mains frequency AC voltage from a DC source such as

a battery. Thus, a power converter according to the invention could be used in a portable power supply for equipment normally operated from the mains. Such a portable power supply would typically include a step-up transformer positioned between the output of the amplifier and the input to the filter. As a result, the transformer would be operating at the higher frequency of the triangle wave.

There have been numerous previous proposals for generating AC voltage from a DC supply. Examples are shown in GB 2248319A and WO-A-88/06814. Neither of these previous proposals suggests carrying out the amplification and transformation at a modulated frequency. This has many advantages. The preferred operation frequency is above 100 kHz. Operation at lower frequencies, such as frequencies below 100 kHz, means that the step-up transformer used is lossy. The inductance of the transformer primary winding is proportional to the frequency and the square of the number of turns per unit length. Hence, at low frequencies for a given inductance (input impedance seen by the power converter) more turns are required. However, the magnetic flux density induced in the transformer core is also proportional to the number of turns per unit length and the current through the primary winding. If the number of turns increases the flux density increases and so do the power losses in the core (due to eddy current etc). Also, with more turns the Joule heating in the primary windings increases. To keep the transformer from melting at high power levels (a power converter according to the present invention can produce power levels of 10 kWs or more) a higher frequency is preferably used for the modulation (triangle wave) and preferably a small compact high efficiency (low power loss) transformer core (typically but not exclusively soft ferrite based). Such transformer cores produce about 1000 times less power losses and hence less heat. The lower number of windings means shorter wires and less Joule heating. It is also possible, in accordance with the present invention, to use several transformers in parallel

whereby to reduce the input current to each transformer and hence the core losses (due to lower flux density) and Joule heating. The use of parallel transformers means that the power output capability can be incremented indefinitely.

All linear amplifiers and current digital amplifiers produce a small amount of noise when there is no signal being amplified. This signal can be from the power amplifier or from the other components of the audio system such as the graphic equaliser / mixer or tape, CD, tuner or record decks. Another aspect of the current invention is the control and elimination of this unwanted signal typically called 'Hiss'. With the inherent low noise of the amplifier (due to precision of triangle wave etc.) it is possible to implement controls to reduce or eliminate this effect. It would be pointless implementing such controls on a noisy amplifier as any input noise that is cancelled would be swamped by the noise generated by the amplifier.

Thus, another aspect of the invention provides an amplifier comprising signal conditioning circuitry for increasing the amplitude of an input signal, wherein the input signal is supplied to a thresholding circuit and the thresholding circuit supplies a disabling signal to the signal conditioning circuitry in the event that the magnitude of the input signal is below a first threshold.

Embodiments of the invention will now be described by way of example only and with reference to the accompanying drawings in which:

Figure 1 is a block circuit diagram of a typical amplifier as known in the art;

Figure 2 is a circuit diagram of a novel triangle wave generator for use in the amplifier of Figure 1;

Figure 3 illustrates a trace of a triangle wave produced by the circuit of Figure 2;

Figure 4 illustrates a least squares fit analysis of the triangle wave of Figure 3;

Figure 5 is a diagram of the magnetic field produced by a current flowing through a wire for the purpose of explaining the novel current sensing means of an amplifier according to the invention;

Figure 6 illustrates the traditional method of sensing current for a single transistor amplifier;

Figure 7 illustrates a current sensing means suitable for use in an example of amplifier according to the invention;

Figure 8 illustrates a possible fabrication of the current sensing means of Figure 7;

Figure 9 shows a well-known "H-bridge" transistor configuration;

Figure 10 is a graph of a typical output pulse for a 2A current in a conductor with a sense coil 2mm in diameter, 2mm from the conductor;

Figure 11 is a circuit diagram of an embodiment of amplifier according to the invention;

Figure 12 is a circuit diagram of anti-hiss circuitry suitable for use with the amplifier of Figure 11;

Figure 13 is a circuit diagram of a power converter incorporating the amplifier circuit of Figure 10; and

Figure 14 is a perspective view of a proposed power generator incorporating the circuit of Figure 10.

Referring firstly to Figure 1, in a typical amplifier, an audio source 1 is amplified by amplifier 2 and compared in a comparator 3 with the output of a triangle wave generator 4 amplified by amplifier 5. The output of comparator mixer 3 is a pulse width modulated signal. The output of the comparator 3 is inverted by inverter 6 and the inverted and non-inverted output of the comparator 3 are supplied to signal conditioning circuitry 7 powered by power supply 8. In order to protect the signal conditioning circuitry from over current, signal sensing circuit 9 senses the current output from signal conditioning circuitry 7 and provides a feedback signal to circuitry 7 whereby to shut off the power in the event of over current.

One of many factors which limits the ability of an amplifier to faithfully reproduce the input waveform is the accuracy of the triangular waveform produced by the triangular wave generator 4 with which the input waveform is mixed. Figure 2 illustrates a novel triangle wave generator which produces a more precise triangular waveform than has been achieved hitherto.

As with a conventional triangle wave generator, an integrator based on operational amplifier IC3A produces a triangular waveform which is then supplied to a second operational amplifier IC3B configured as a comparator. Comparator IC3B produces a square wave from the output of integrator IC3A and this is then fed back into the integrator IC3A to produce a triangular waveform. The accuracy and linearity of the final triangle wave is determined by how clean and sharp is the

square wave produced from comparator IC3B. In practice, the comparator IC3B cannot respond instantaneously and hence, the vertical edges of the square wave do not rise sharply at 90° but at a lesser angle. On the top of the square wave the transition from the vertical to horizontal edges should again ideally be 90°. In practice, there is a rounding off of the transition or if the comparator does not settle, it can overshoot and then under shoot until it settles at the higher level of the square wave. These deficiencies in the basic square wave are transformed into non-linearities in the triangle wave and either "rounding over" or excessive "peaking" at the transitions between the positive and negative slopes of the triangle wave. When such a basic triangle wave is used as a basis for an amplifier, then the incoming signal is severely distorted by the amplifier. The triangle wave would only be usable over a limited proportion of its range and typically the triangle wave frequency would have to be limited.

To overcome the deficiencies of the basic triangle wave generator, the circuit shown in Figure 2 uses two logic gates IC4A and IC4B. These logic gates are designed to swing between equal positive and negative supply voltages at high speed with minimum overshoot or rounding. The resulting "cleaned-up" square wave gives an improved reference that produces a more precise triangle wave. In the illustrated example, two CMOS AND gates are used. Two are provided in order to cancel the inversion caused by only one. Any other bistate device could be used. Such devices are non-linear and rapidly switch between states. The result is a more precise square wave with no rounding, overshoot and minimum slew.

Figure 3 shows a trace of the triangle wave as produced on an oscilloscope.

Figure 4 illustrates the residuals from a least squares fit of a straight line to the

positive slope, from which the linearity of the trace is evident. The residuals show a random distribution which is mainly due to the measuring instruments used. The worst case deviation from a straight line is less than 0.5%.

Referring back to the circuit diagram of Figure 2, a further amplifier based on IC5A is used to amplify the triangle wave. A variable resistor VR1 connected to the non-inverting input of IC5A is used to adjust and cancel out any DC offsets. A further variable resistor VR2 connected to the non-inverting input of IC3A is used to adjust the mark to space ratio and hence ensure that the positive slope is equal and opposite to the negative slope. Having the offset adjustment separate from the triangle and square wave generators ensures that the offset and mark to space ratio adjustments are independent. Variable resistor VR1 and/or variable resistor VR2 may be laser trimmed during manufacture for greater precision of the triangle wave.

An important advantage of this design of triangle wave generator is its ability to operate at high frequencies. A general characteristic of triangle wave generators is that departures from the accurate triangular waveform are more significant at higher frequencies. Therefore, the more accurate the waveform, the more suitable is the generator for operation at high frequencies. For an audio amplifier with a flat passband from 20Hz to 20kHz, the switching frequency needs to be at least 100 kHz and ideally greater than 200 kHz otherwise the higher frequency response of the amplifier will be degraded. The triangle wave generator described above operates satisfactorily in the frequency range above 200kHz. In fact one design has been run with standard comparators in excess of 1 MHz. However, as the frequency is increased, the demands placed on the other parts of the amplifier circuit, in particular the signal conditioning circuitry 7, becomes more severe. Therefore, a flexible and fast responding current sensor is necessary and one such

sensor will be discussed in more detail below.

Figure 5 illustrates the well-known phenomenon whereby a current flowing through a wire generates a magnetic field surrounding the wire. The size of the magnetic field is related to the size of the current. Thus, if the magnetic field could be accurately measured, this would be a useful method for current sensing.

Ampere's law relates the magnetic field and the current as follows:

$$B.2\pi r \equiv \frac{I}{\varepsilon c^2}$$

Where r is the radial distance from the centre of the conductor.
ε is the permittivity of free space (assume measurement in air).
I is the current flowing in the conductor.
c is the speed of light (assume in vacuo).

Then $$B \equiv \frac{1}{4\pi r \varepsilon c^2} 2I$$

From the above it is evident that the induced magnetic field at a given distance from the conductor is directly proportional to the current flow in the conductor. If a single coil of wire is placed adjacent to the conductor such that the radial magnetic field cuts through the area of the coil then a voltage will be induced in the coil and associated circuitry. The relationship between the induced emf and the field is given by Faraday's law.

$$\xi \equiv -\frac{\partial \phi}{\partial t}$$

where ξ is the induced emf

ϕ is the magnetic flux through the single coil

t is the time

Hence, the induced emf is proportional to the rate of change of magnetic flux through the single coil. The flux through a coil is the measure of the magnetic field strength i.e. density of field lines, such that:

$$\phi \equiv \int_{inside\_a} B \bullet n \partial a$$

where n is a vector normal to the area inside the coil

The integral is over the area of the coil a.

Then, if the coil is positioned such that the coil subtends the radial field normally the flux can simply be written as:

$$\phi = B.a$$

and the induced emf can be related to the radial field induced by the current flowing in the conductor by:

$$\xi \equiv -a.\frac{\partial B}{\partial t}$$

The area of the coil is constant, so the induced emf and current flowing in the conductor is given by:

$$\xi \equiv -\frac{2a}{4\pi\varepsilon c^2}\frac{\partial I}{\partial t} \qquad \text{(A)}$$

One problem with the above relationship is that the induced emf is proportional to the rate of change of current, not directly to the actual steady state current.

However, this problem can be easily overcome when the current is flowing through the output stage of a transistor based amplifier, as the following explanation will show.

Figure 6 illustrates a single transistor amplifier.

Here, a positive input signal applied to the drive terminal S3 will turn on (start conducting) the transistor Q1 and current will flow from the rail supply V+, S1 down to ground GND, S2. To monitor the current from S1 to S2 when the transistor is turned on the traditional method places a small value resistor in series with the lower transistor connection (source in this example) and ground. By Ohm's law the current flowing through this resistor generates a voltage across the resistor and this voltage is then amplified and used as a current measure. The current is related to the measured voltage by the simple expression:

$$I \equiv \frac{V}{RA}$$

where V is the measured voltage
R is the sense resistor value
A is the gain of the circuitry used to condition the voltage

generated across the sense resistor.

This approach has a number of inherent disadvantages which are:

Dissipates power – inclusion of the resistor adds a load and reduces the overall efficiency of the system.

Low value resistors can be troublesome - to reduce the power dissipated the resistance value is kept low, these values can be difficult to reproduce reliably (including stray resistance).

Couples supply noise to control circuits – if the load is highly inductive the inductive noise spikes are coupled back to the control circuits.

One feature of the above circuit is the series resistor from S2 to the control junction of the transistor (in this case the gate). This resistor in conjunction with the input capacitance of the transistor limits how fast the transistor can be turned on. Hence, because the rate that the transistor is turned on is controlled, the rate of change of current through the conductor from the low terminal of the transistor (source in this example) to ground is also controlled. Then, from equation (A) above, if the signal induced in the sense coil is amplified and subsequently integrated for a time greater than the turn-on time of the transistor, the result is a voltage related directly to the current flowing through the conductor independent of the rate of change of current.

A complete signal sensing circuit is illustrated in Figure 7. The circuit begins with the basic single sense coil 20 which detects the magnetic field from the current as the output amplifier is switched on. The initial impulse signal is first

amplified by amplifier 21 and then integrated by integrator 22 as described above to produce a signal related to the current and independent of the rate of current change. The integrated signal is then compared in comparator 23 with a reference threshold from reference generator 24 such that if the measured signal is greater than the threshold a pulse is output from the comparator.

Because the switching amplifier configuration switches within the period of the triangle wave, the output current is repeatedly sampled on each pulse output of the amplifier (in effect 100,000s times per second). To produce a broader pulse that will shut down the amplifier output on each turn-on cycle the current sense signal is fed into a monostable 25. This gives the ability to shut down the amplifier output when an over current is detected for one triangle wave period or multiple triangle wave periods. The signal from the monostable 25 is fed directly to the inhibit input of the output transistor drive circuitry.

For high current applications where local amplification is used there is sufficient sensitivity afforded by a single coil. The single coil has other benefits namely:

It has minimum inductance and hence, will be fast responding (this is an important feature for the control function).

It dissipates no significant power and hence, is ideally suited to high current sensing applications. In fact, the sensitivity of the method increases with increasing current being sensed.

The single coil is easy to fabricate in all substrate manufacturing technologies.

It is easy to fabricate the coil such that it is sandwiched between two ground planes which minimises any local electrostatic noise coupling.

It occupies minimal space.

It is achieved with virtually no additional cost to the overall control circuits.

A practical arrangement of the current sense coil and the current carrying conductor is shown in Figure 8.

The single sense coil 20 is printed adjacent to the current carrying conductor 30 on a base substrate layer 31. Conducting vias 32 connect the coil 20 through second substrate layer 33 to conductive tracks 34 leading to electronic processing circuitry as shown in Figure 7. Top and bottom metallisation layers 35, 36 minimise electrostatic noise coupling.

In the illustration a simple laminar substrate technology such as standard multi-layer PCB or direct bonded copper (DBC) substrate is shown. The technique is applicable to other substrate technologies such as ceramic thick film hybrids. With a hybrid the secondary substrate layer is replaced with a screen printed glass insulating layer over the coils. A further metallisation layer can then be screen printed over the glass layer. Similar processes can be adopted to fabricate the structure using thin film deposition or other methods. The electronic processing circuitry is omitted here for clarity.

In the current version of the amplifier the signal conditioning circuitry is built using discrete transistors which affords low cost and a rapid speed of response

(this is not an essential requirement but it produces the maximum benefit from this method). The pulse current monitor can respond in a time period approaching 100ns. This is equivalent to the switch–on time of the output transistors. Therefore the current monitor can respond effectively instantaneously to an over-current condition.

With the combination of output transistors used in the classical 'H bridge' format, the transistors are switched on in 'high' and 'low' side pairs as shown in Figure 9.

In the H bridge switching circuit 40, to produce bi-directional current flow through the load (across OUT 1 and OUT 2) the output transistors are operated in pairs. If TR1 and TR4 are one pair, and TR2 and TR3 are the other pair. The transistors in each pair should be switched on and off simultaneously. However, due to component manufacturing tolerances there will be a slight imbalance in the turn-on and turn-off times of each transistor. This will be apparent at high switching rates. This can mean that one transistor in a pair could still be switched on when the other pair of transistors are being turned on. In this condition 'shoot through' occurs and a very large, direct current flows between the transistors independent of the load. Due to the inherent high speed of response the single coil current sensor can monitor and react to this condition shutting down the drive to the MOSFET.

A typical output pulse is shown in Figure 10 for a 2A current in a conductor with a sense coil 2mm in diameter, 2mm from the conductor.

The signal above shows the response to the pulsed current after sensing by the coil and initial amplification.

Figure 11 illustrates an example of an audio amplifier according to the present invention. Components already described above have been given like reference numerals and will not be described again herein. Comparing Figure 11 to Figure 1, it will be noted that the signal sensing circuit 9 has been replaced by the circuit of Figure 7. The signal conditioning circuitry comprises the H bridge switching circuit 40 together with a pair of MOSFET drive circuits 41, 42. The signal conditioning circuit comprising components 40, 41, 42 requires only a unipolar power supply from power supply converter 50 . Power supply converter 50 includes a small regulator, not shown, to provide a small negative voltage for components 2, 3, 4, 5 and 6. The high efficiency of the amplifier as a whole resulting from the improvements described above means that only a unipolar input supply is required by converter 50.

The circuit of Figure 11 would be suitable for driving a loudspeaker of a sound system. The audio source 1 could be taken from a CD, radio, microphone, record, tape source etc. at a signal level of up to 1V peak to peak. The signal could then be amplified and using just one amplifier module up to 1000W of audio power can be used to drive the output speaker(s).

In practice, a filter, not shown, would filter out the modulation frequency before the outputs from the circuit 40 were supplied to loudspeakers.

Figure 12 is a block diagram including the anti-hiss circuitry for use with an audio amplifier. The output from differential amplifier 2 (see Figure 11) is coupled to a high gain amplifier 70. This boosts the signal amplitude such that any input noise is easily resolved. The signal is then full wave rectified by rectifier 71 such that only the magnitude not the polarity of the signal is determined. This function ensures that the circuitry responds equally to positive or negative noise signals.

The magnitude signal is then coupled to a sample and hold, peak value circuit 72. This circuit is arranged such that the response to the input signal is effectively instantaneous, but then holds the peak value of the signal for a pre-determined period of time. This time period is the delay before the anti-hiss correction is activated. The signal is then coupled to a comparator 73 which compares the signal level with a threshold level supplied from threshold generator 74. The threshold could be a simple voltage reference or could be dynamically adjusted such that for different tracks of audio sources the threshold level is varied. If the sampled signal is below the threshold the output from the comparator 73 disables the drive to the power output stage of the amplifier. Because the output stage comprising a classic 'H bridge' is fully disabled then no signal is produced by the amplifier and no hiss will be coupled to the speaker network.

Another feature of this scheme is that an additional comparator can be used to detect that the signal is below a higher threshold level. If the signal is above this second threshold the input amplitude will be too high. In this case either the drive is disabled to prevent speaker damage or additional gain control circuitry could be used (not shown on diagram) to reduce automatically the input signal level. In conventional amplifiers this scenario is typically handled by allowing the input signal to clip which produces distortion and is not sympathetic to the loudspeakers. In addition the operation of the mosfet drivers are delayed for a few seconds during power up to prevent surges from reaching the speakers.

With the capability to produce a single supply, highly efficient, low distortion amplifier with an integral current monitor, other applications become feasible. One such application is a power conversion module that takes a DC voltage and produces an AC output. An illustration of a power conversion circuit is shown in Figure 13. In Figure 13, the audio input 1 has been replaced by a precision sine

wave generator 60. The output from the switching circuitry 40 could be supplied to a transformer 65 followed by filtering at filter 66 to filter out the amplitude modulation frequency of triangle wave generator 4. The output from the filter 66 is a high voltage replica of the original sine wave from sine wave generator 60.

The circuit of Figure 13 could be used in numerous applications where it is required to generate AC voltages from DC supplies. Other applications include generation of mains supplies from renewable energy sources (fuel cells, wind, solar, tidal)
AC traction from DC power sources,
Generation of low distortion mains supplies
Portable mains supplies.

The final example listed above could comprise a battery powered power supply providing an output voltage which replicates the AC mains supply. In this case generator 50 would generate a sine wave at 50 Hz. Figure 13 is an example of what such a power supply might look like.

Figure 14 simply illustrates a box 100. Inside the base of the box would be one or more batteries. These could be lead-acid car batteries or other rechargeable power cells. Potted into the lid of the box would be the power converter including the output transformer. The mains connector on top of the box could have an integral residual current circuit breaker fitted and would ideally be sealed to prevent water ingression in use.

Claims:

1. A triangle wave generator comprising a comparator and an integrator, the output of the comparator being supplied to the integrator and the output of the integrator being supplied to the comparator whereby the output of the comparator is a square waveform and the output of the integrator is a triangular waveform, wherein the output of the comparator is supplied to the integrator via one or more bistate devices.

2. A triangle wave generator as claimed in claim 1 wherein the bistate device(s) is/are arranged in a non-inverting configuration.

3. A triangle wave generator as claimed in claim 1 or 2 wherein the bistate device(s) is/are CMOS device(s).

4. A triangle wave generator as claimed in any preceding claim in which the bistate device(s) is/are logic gates(s).

5. A triangle wave generator as claimed in claim 4 in which the logic gate(s) is/are AND gate(s).

6. A triangle wave generator as claimed in any preceding claim in which the output of the integrator is supplied to DC offset adjustment means.

7. A triangle wave generator as claimed in claim 6 in which the DC offset adjustment means comprise a variable resistor.

8. A triangle wave generator as claimed in any preceding claim in which means are provided for adjusting the mark/space ratio of the triangular waveform.

9. A triangle wave generator as claimed in claim 8 in which said adjustment means comprise a variable resistor connected to the input of the integrator.

10. An amplifier including a triangle wave generator as claimed in any preceding claim.

11. A power convertor including a triangle wave generator as claimed in any preceding claim.

12. An amplifier comprising signal conditioning circuitry including at least one transistor, in which means are provided for sensing the current through the transistor, said current sensing means comprising an inductor positioned adjacent a conductor carrying the current to be sensed and an integrator arranged to integrate the current.

13. An amplifier as claimed in claim 12 in which the integrator is arranged to integrate the current flowing through the inductor for a time greater than the turn-on time of the transistor.

14. An amplifier as claimed in claim 12 or 13 in which the inductor is a single conductive loop.

15. An amplifier as claimed in claim 12, 13 or 14 in which the inductor and the conductor are printed on a substrate.

16. An amplifier as claimed in any of claims 12 to 14 including means for switching off the amplifier in the event that the output from the integrator exceeds a predetermined threshold.

17. An amplifier as claimed in any of claims 12 to 14 including a triangle wave generator as claimed in any of claims 1 to 5 providing a carrier signal for a signal to be amplified.

18. A power convertor including an amplifier according to any of claims 12 to 17.

19. A power convertor for generating an AC voltage from a DC supply comprising a sine wave generator operating at the desired frequency of the AC voltage, a triangle wave generator operating at a higher frequency than the sine wave generator, means for mixing the outputs of the sine wave and triangle wave generators to produce an pulse width modulated signal at the higher frequency, an amplifier for amplifying the pulse width modulated signal and a filter for filtering out the higher frequency.

20. A power convertor as claimed in claim 19 including a DC source supplying voltage to the triangle and sine wave generators.

21. A power convertor as claimed in claim 20 further comprising a step up transformer for increasing the voltage output from the amplifier before it is supplied to the filter.

22. A power convertor as claimed in claim 19, 20 or 21 in which the triangle wave generator is as claimed in any of claims 1 to 7.

23. A power convertor as claimed in any of claims in which the amplifier is as claimed in any of claims 10 to 14.

24. An amplifier comprising signal conditioning circuitry for increasing the amplitude of an input signal, wherein the input signal is supplied to a thresholding circuit and the thresholding circuit supplies a disabling signal to the signal conditioning circuitry in the event that the magnitude of the input signal is below a first threshold.

25. An amplifier as claimed in claim 24 in which the thresholding circuit supplies a disabling signal to the signal conditioning circuitry in the event that the magnitude of the input signal is above a second threshold.

26. An amplifier as claimed in claim 24 or 25 in which the input signal is amplified before being supplied to the thresholding circuit.

27. An amplifier as claimed in claim 24, 25 or 26 in which the input signal is rectified before being supplied to the thresholding circuit.

28. An amplifier as claimed in any of claims 24 to 27 in which the means are provided for dynamically adjusting the first threshold.

29. An amplifier as claimed in any of claims 24 to 28 including a triangle wave generator as claimed in any of claims 1 to 9.

30. An amplifier as claimed in any of claims 24 to 29 and as claimed in any of claims 10 and 12 to 17.

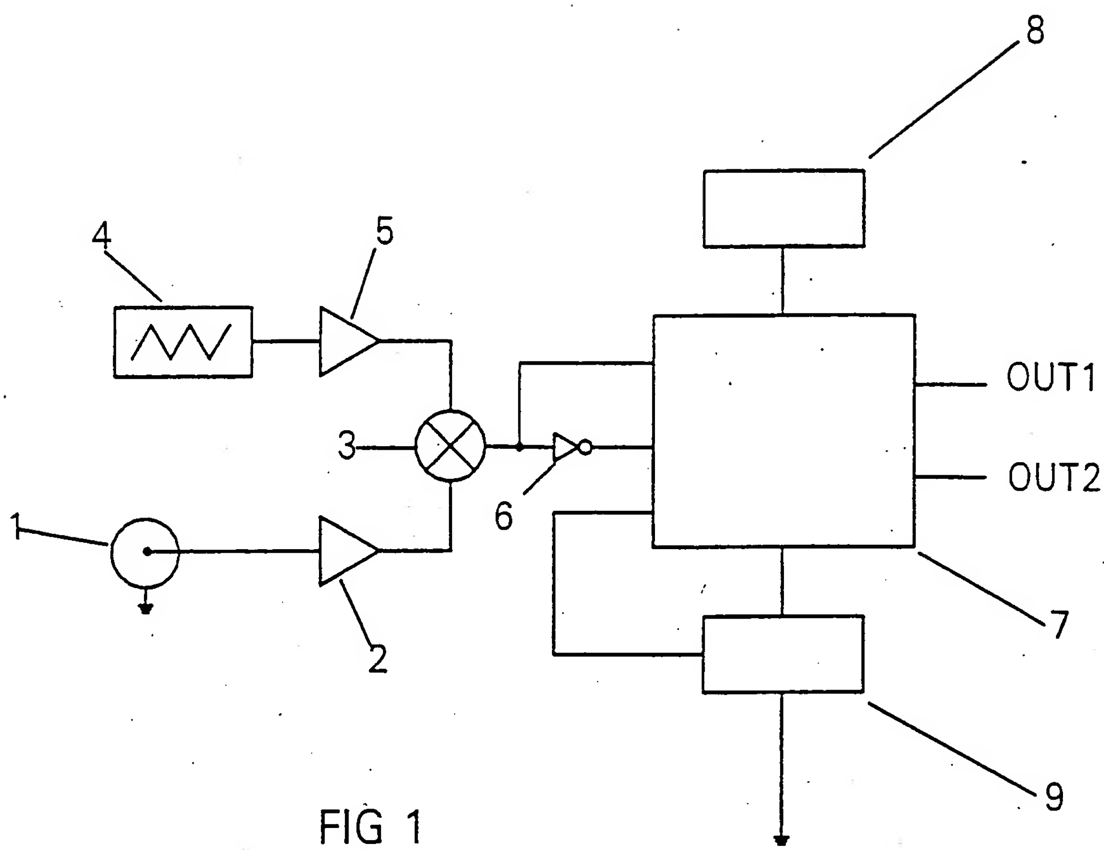

FIG 1

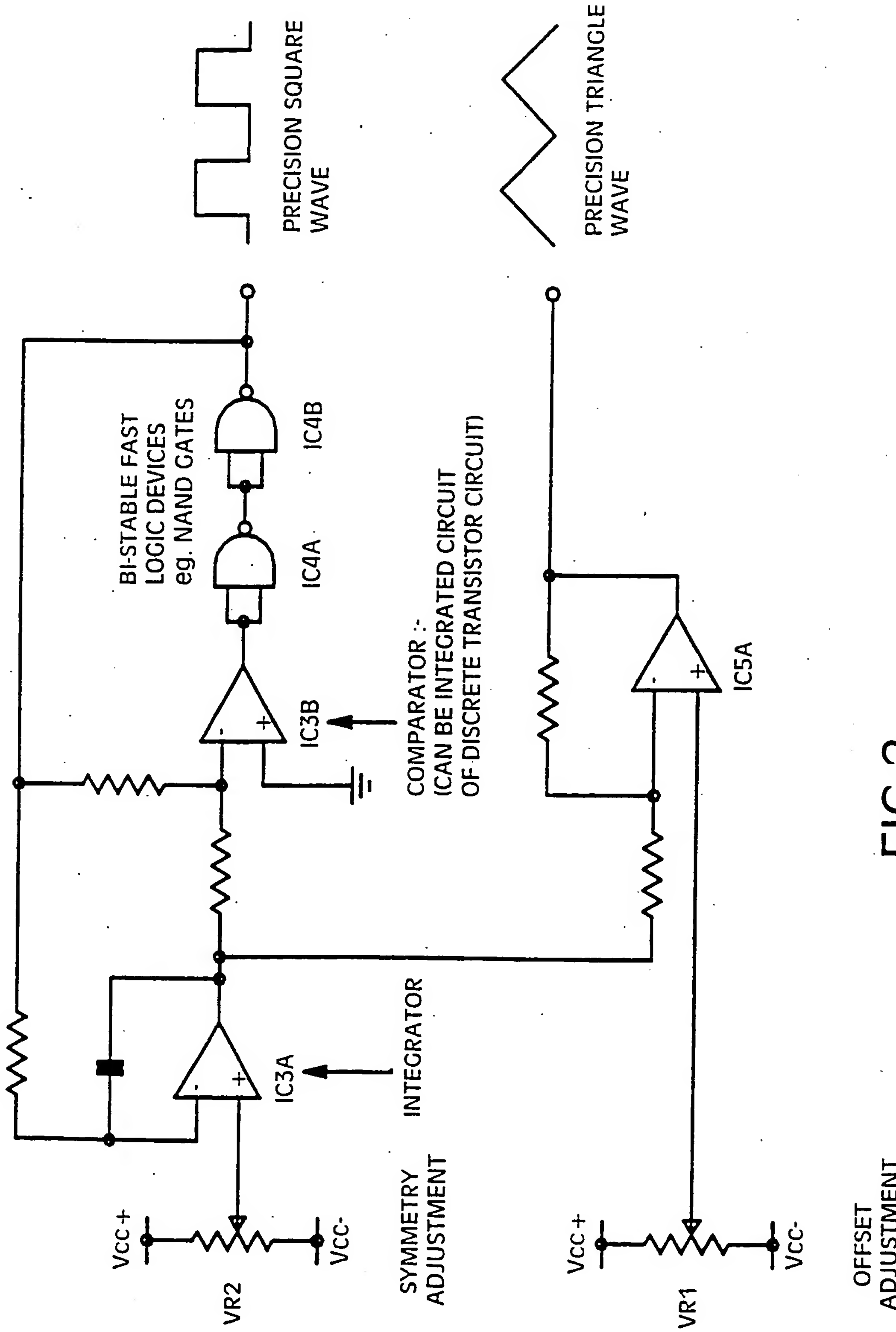
PRECISION SQUARE WAVE
PRECISION TRIANGLE WAVE
BI-STABLE FAST LOGIC DEVICES eg. NAND GATES
IC4A
IC4B
COMPARATOR :- (CAN BE INTEGRATED CIRCUIT OF DISCRETE TRANSISTOR CIRCUIT)
IC3B
IC5A
INTEGRATOR
IC3A
Vcc+
Vcc-
VR2
SYMMETRY ADJUSTMENT
Vcc+
Vcc-
VR1
OFFSET ADJUSTMENT

FIG 2

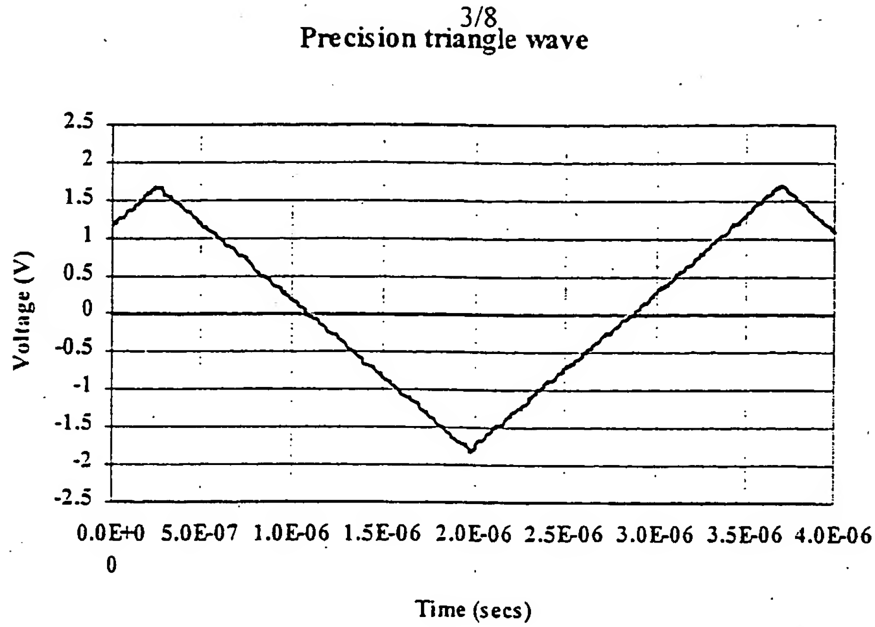
Precision triangle wave
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Voltage (V)
0.0E+0
0
5.0E-07
1.0E-06
1.5E-06
2.0E-06
2.5E-06
3.0E-06
3.5E-06
4.0E-06
Time (secs)

FIG 3

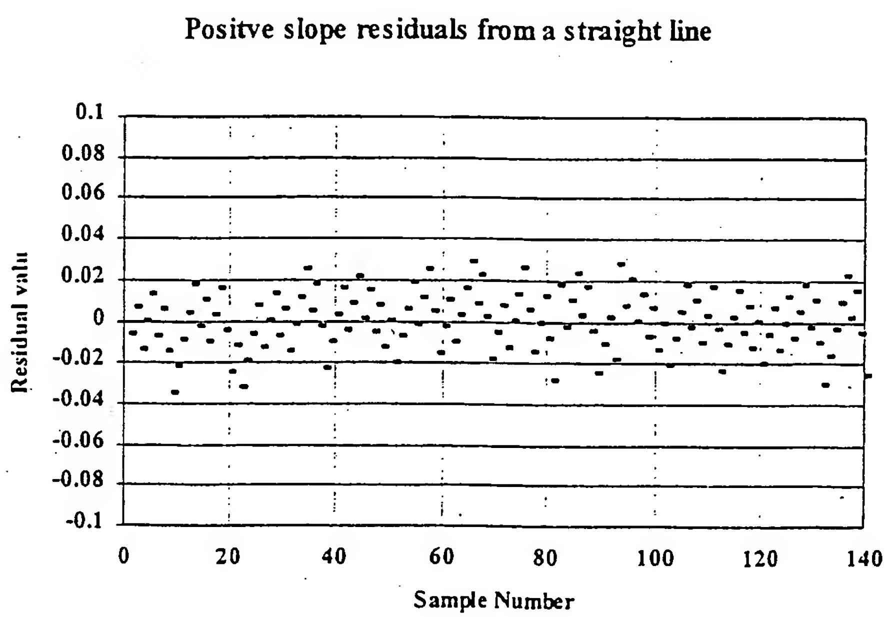
Positve slope residuals from a straight line
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
Residual valu
0
20
40
60
80
100
120
140
Sample Number

FIG 4

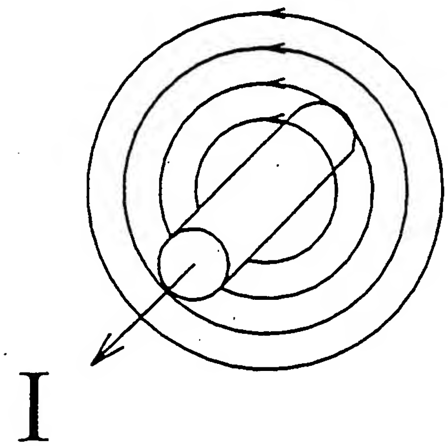

FIG 5

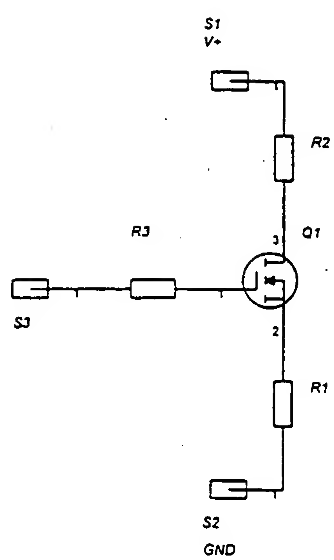

FIG 6

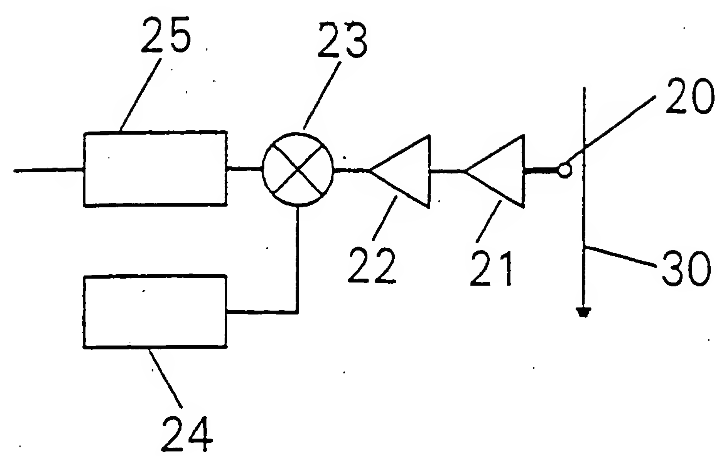

FIG 7

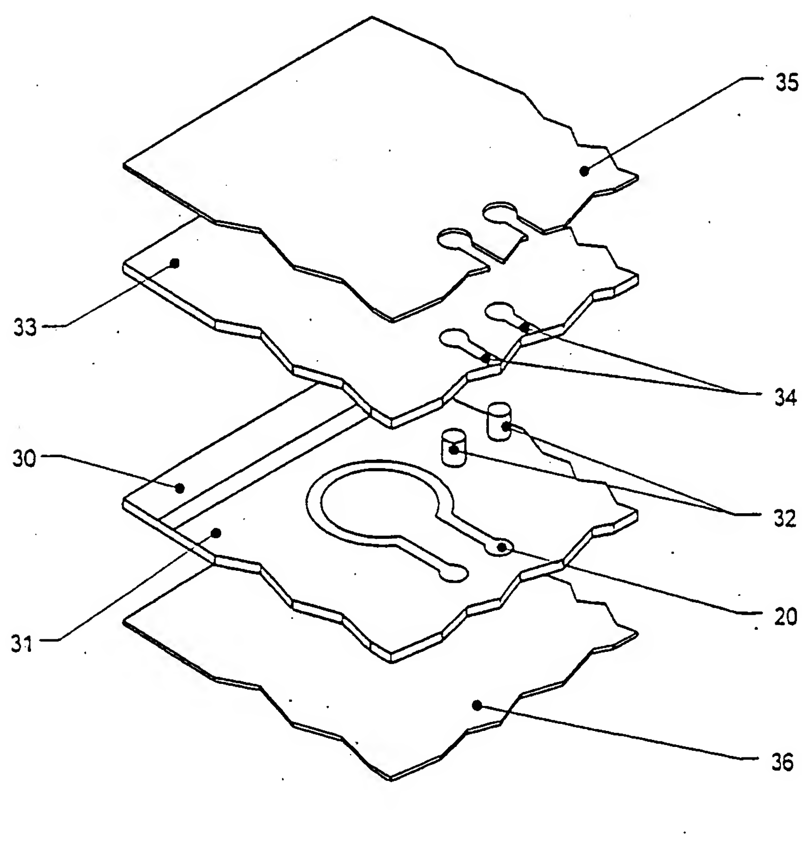

FIG 8

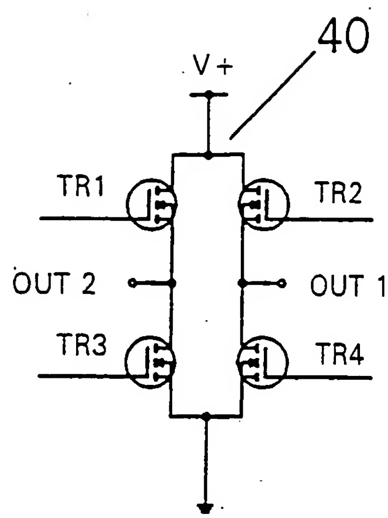
40
V+
TR1
TR2
OUT 2
OUT 1
TR3
TR4

FIG 9

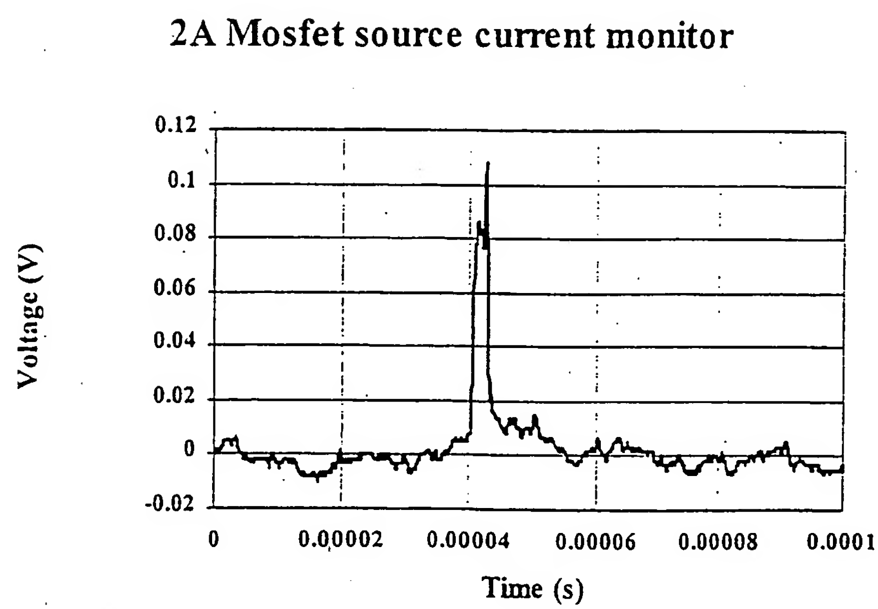
2A Mosfet source current monitor
Voltage (V)
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
0.00002
0.00004
0.00006
0.00008
0.0001
Time (s)

FIG 10

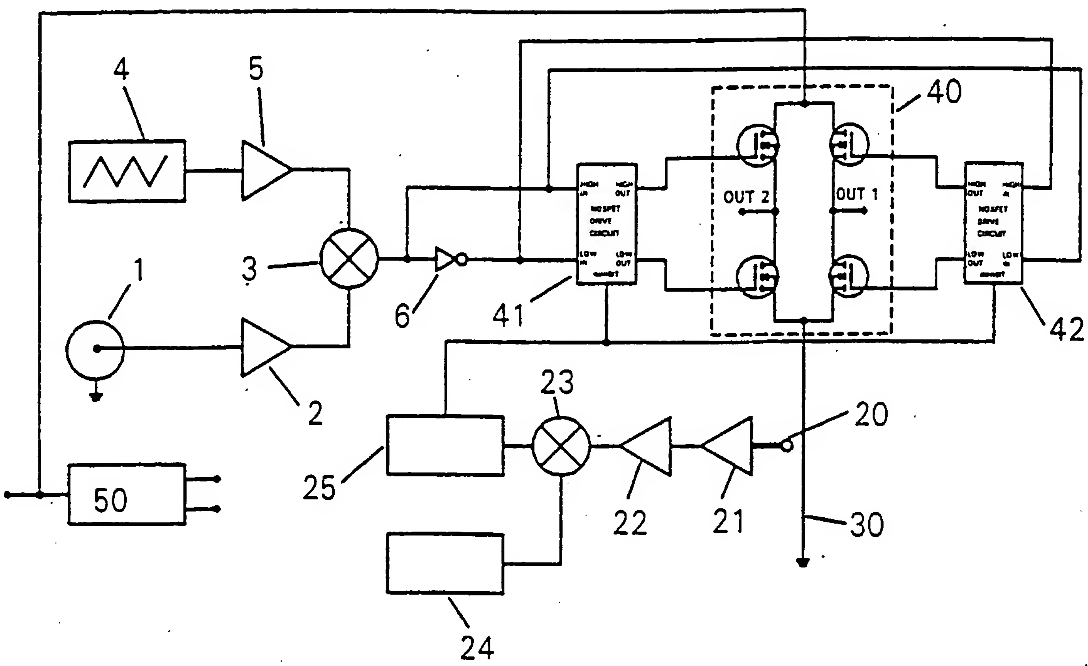

FIG 11

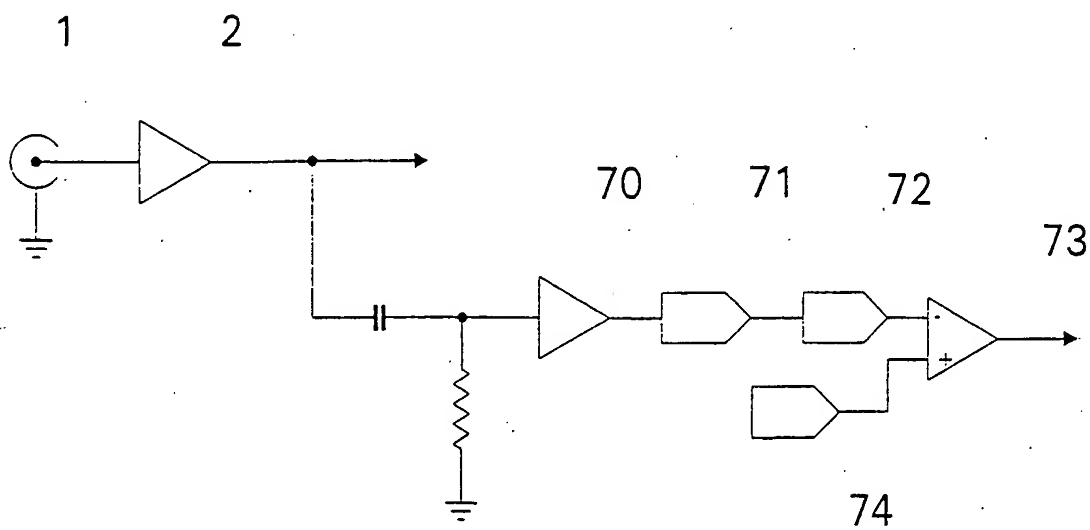

FIG 12

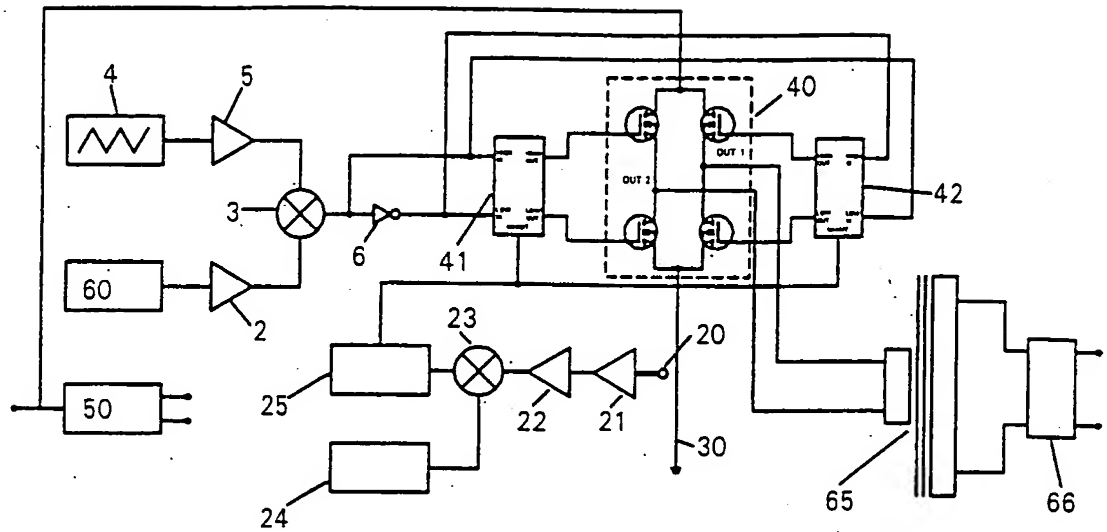

FIG 13

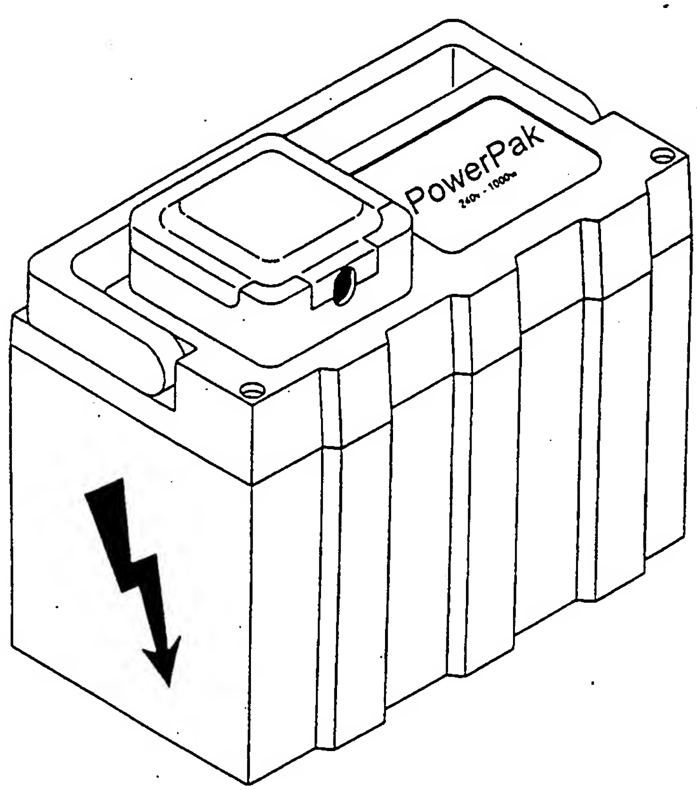

FIG 14

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/02542

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H03K4/06 H03K17/08 H02M1/00 H03G3/20 H03F3/217

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H03K H03G H03F H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, IBM-TDB, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	"VOLTAGE-CONTROLLED OSCILLATOR" ELEKTOR ELECTRONICS,GB,ELEKTOR PUBLISHERS LTD. CANTERBURY, vol. 15, no. 169, 1 July 1989 (1989-07-01), page 31,1 XP000098184 ISSN: 0268-4519 the whole document	1-11

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 December 2000	18.12.00

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Moll, P

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/02542

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CURTIS R ET AL: "ANALOG RAMP GENERATOR FOR A FAST SCANNING TUNNELING MICROSCOPE" REVIEW OF SCIENTIFIC INSTRUMENTS, US, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, vol. 65, no. 10, 1 October 1994 (1994-10-01), pages 3220-3223, XP000474225 ISSN: 0034-6748 figure 3	1-11
X	US 4 782 287 A (MARX THOMAS I) 1 November 1988 (1988-11-01) column 4, line 58 -column 5, line 25; figure 1	1-11
Y		17,22
X	US 4 015 140 A (MILKOVIC MIRAN) 29 March 1977 (1977-03-29) column 4, line 43 -column 5, line 23; figures 1,3A,3D,4 column 6, line 24 -column 7, line 55	1-5,8, 10,11
X	US 4 323 862 A (BOUDAULT ROBERT ET AL) 6 April 1982 (1982-04-06) the whole document	1-4,6,8
X	SHKARUPIN V V: "CIRCUIT TAILORS TRIANGLE WAVEFORMS" ELECTRONIC DESIGN, US, PENTON PUBLISHING, CLEVELAND, OH, vol. 39, no. 20, 24 October 1991 (1991-10-24), pages 109-110, XP000255088 ISSN: 0013-4872 the whole document	1,6-9
X	US 4 296 413 A (MILKOVIC MIRAN) 20 October 1981 (1981-10-20) column 3, line 20 -column 6, line 13; figure 1	1-4,6
X	US 3 697 891 A (SHADE ROSS A ET AL) 10 October 1972 (1972-10-10) column 2, line 42 -column 4, line 22; figure 1	1
X	US 3 609 512 A (LEWIS EDWARD E) 28 September 1971 (1971-09-28) column 2, line 3 -column 4, line 68; figure 1	12-14,16
X	US 4 270 164 A (WYMAN KENNETH R ET AL) 26 May 1981 (1981-05-26) column 7, line 54-66; figure 6	12,16

-/--

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	DE 196 09 457 A (HEBENSTREIT ERNST DIPL ING) 25 September 1997 (1997-09-25) the whole document	12,13,16
X	DE 41 37 277 C (ANT NACHRICHTENTECHNIK GMBH) 21 January 1993 (1993-01-21) column 3, line 30-58; figure 4	12,16
X	US 4 757 434 A (KAWABATA TAKAO ET AL) 12 July 1988 (1988-07-12) column 3, line 12-48; figures 2,3A	12,13, 18-21,23
Y		17,22
X	US 4 660 137 A (HOTAKA NOBUHIRO) 21 April 1987 (1987-04-21) column 3, line 14 -column 4, line 62; figures 3,6	19-21
X	US 4 390 940 A (CORBEFIN RENE ET AL) 28 June 1983 (1983-06-28) column 3, line 32 -column 5, line 46; figures 1-4	19-21
X	US 5 307 407 A (WENDT ROLF H G ET AL) 26 April 1994 (1994-04-26) column 3, line 60 -column 5, line 39; figure 1	19,20
X	US 5 257 174 A (OGIWARA KAZUYUKI ET AL) 26 October 1993 (1993-10-26) column 7, line 17 -column 10, line 19; figure 4	19,20
X	EP 0 301 483 A (TOKYO SHIBAURA ELECTRIC CO) 1 February 1989 (1989-02-01) column 3, line 40 -column 5, line 24; figures 1,3	19,20

2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/GB 00/02542

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
   because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☒ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

   1-23

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-11

   Triangle wave generator comprising a comparator, an integrator and one or more bistate devices.

2. Claims: 12-18

   Amplifier comprising an inductor for sensing the current through a transistor.

3. Claims: 19-23

   Power converter for generating an AC voltage from a DC supply.

4. Claims: 24-30

   Amplifier circuitry for disabling its voltage gain when the input signal is below/above predetermined signal levels.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 00/02542

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
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US 4015140	A	29-03-1977	US	3947763	A	30-03-1976
			CA	1035839	A	01-08-1978
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			JP	3253220	A	12-11-1991
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			CA	1311550	A	15-12-1992
			DE	3888256	D	14-04-1994
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